GROUNDWATER IN PERMAFROST REGIONS OF CANADA

BY

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Abstract

Evidence of groundwater flow systems is found in Canada's permafrost regions in the form of springs (thermal, non-thermal, mineral and non-mineral), associated icings or aufeis, open-water reaches in rivers in winter, contributions to baseflow and to dissolved-mineral content of streams, and concentrations of halophytic vegetation.

Little use is made of groundwater for either domestic or industrial supply in northern Canada at present, and its potential in this respect has hardly been explored. Reliable supplies are available in a number of areas from unconsolidated gravels or sands, or from sandstones, carbonates, or fractured crystalline rocks where these are not frozen. Water from the active layer usually carries appreciable organic content; water from unfrozen karst systems in or near the mountains, and from unfrozen gravels often is of good quality; deeper groundwater may range in quality from fresh to salt.

Apart from its water supply potential, groundwater has an essential role in enabling fish populations to survive in northern streams, and groundwater discharge areas are often a source of trouble in construction and maintenance of engineering projects. Quick conditions, frost heaving, slope failures, active formation of ice lenses, and buildup of aufeis may all occur naturally or they may be induced through changes in groundwater flow patterns caused by engineering development.

The water-supply, engineering and fisheries aspects of groundwater in the permafrost region all need further study, not only in terms of inventory (e.g. of springs, discharge areas and potential aquifers), but also to gain a wider understanding of the interaction between groundwater systems and engineering developments.

Résumé

Les systèmes d'écoulement d'eaux souterraines se manifestent dans les régions canadiennes de pergélisol sous forme de sources (thermales, non thermales, minérales et non minérales), de phénomènes connexes de congélation ou de buttes en lentilles de glace, de tronçons de d'un cours d'eau dégagés de glace en hiver, d'apports à l'écoulement de base et au contenu de minéraux en dissolution dans les cours d'eau ainsi que de concentrations d'halophytes.

A l'heure actuelle, on se sert très peu, dans le Nord canadien, des eaux souterraines pour l'approvisionnement domestique et industriel, et les possibilités à cet égardont été à peine étudiées. Des stocks sûrs sont disponibles dans bon nombre de régions où se trouvent des dépôts non gelés de gravier ou de sables meubles, de grès, de carbonates, ou de roches cristallines brisées. L'eau contenue dans la couche active transporte d'habitude des matières organiques appréciable; celle qu'on trouve dans les régimes karstiques non gelés, situées à l'intérieur ou à proximité des montagnes, et dans le gravier non gelé est de bonne

qualité. Quant aux eaux souterraines plus profondes, elles peuvent être douces ou salées.

En plus de son potentiel d'approvisionnement, l'eau souterraine joue une rôle essentiel dans la survie des populations de poissons du Nord. Les régions de déversement des eaux souterraines posent souvent des problèmes dans la construction et l'entretien des installations techniques. Le changement rapide des conditions, les poussées verticales de gel, les ruptures de pente, ainsi que la formation active de lentilles de glace et d'hydrolaccolithes, sont tous des phénomènes de la nature, main peuvent aussi être provoqués par la modification du régime d'écoulement des eaux souterraines à la suite d'aménagements techniques.

Les aspects des eaux souterraines concernant l'approvisionnement en eau, l'aménagement technique et les pêches dans les régions pergélisolées doivent être étudiés plus en profondeur, non seulement pour établir un inventaire des sources, des régions de déversement et des aquifères potentiels, mais aussi pour acquérir une meilleure compréhension de la corrélation entre les régimes d'eaux souterraines et des développements techniques.

Introduction

Directions, rates and extent of groundwater movement in the permafrost areas of Canada are, in general, dependent on the same physical parameters as in more temperate regions that lack permafrost. These include: seasonal and areal distribution of water available for recharge; topography and morphology, which determine the available potential for groundwater movement; and geology, including lithology and structure, which determines the distribution of permeability and storage capacity and locally preferred directions of movement.

Over a large portion of Canada's permafrost region the mean annual precipitation is low. It ranges from 300 to 400 mm in the southern part of the Yukon, the southwestern portion of the District of Mackenzie, southern Baffin Island and northern Labrador, to less than 100 mm over the western part of the Arctic Islands. This severely restricts the availability of water for recharge.

In addition to the limited input available, the low mean annual air temperatures and the presence of perannially frozen ground impose restrictions to recharge that do not exist, at least not to the same extent, in more temperate regions. Longer periods with temperatures below 0°C maintain the active layer in frozen condition for up to 10 months. Thawing in the active layer may thus be limited to as little as 2 months each year. Although Harlan (1972) and others have shown that recharge can take place through frozen ground under the appropriate conditions, the recharge rates involved usually are one or more orders of magnitude lower than those for non-frozen ground.

Permafrost, where present, constitutes a permanent low-permeability layer, discontinuous in the southern fringe of the permafrost region, and gradually becoming more continuous and increasingly thick farther north. As a result the presence of permafrost has a significant, but regionally and locally variable, influence on:

1. recharge to deeper aquifers, even during maximum thaw penetration in the active layer;
2. rates of groundwater movement;
3. spatial distribution of groundwater movement;
4. possibilities for groundwater discharge.

Furthermore, the restrictive influence of permafrost containing extensive segregated ice (as layers, lenses or wedges) is considerably increased over that of frozen ground containing only pore-ice, due to negligible permeability of the ice.

The restriction of infiltration and recharge of groundwater leads to the presence of extensive muskegs and numerous lakes and ponds in this generally water-deficient area where mean annual evapotranspiration exceeds mean annual precipitation. Many of the larger lakes and rivers have unfrozen zones (taliks) of variable horizontal and vertical extent associated with them. Some of these penetrate the permafrost, presenting opportunities for either recharge or discharge of groundwater.

Relatively little research is being done on groundwater problems in the permafrost region in Canada. Evidence for this can be seen in the Proceedings of the Second International Conference on Permafrost, held in Yakutsk, USSR in July, 1973. Of a total of 28 technical papers on groundwater in permafrost, 22 originated in the USSR, 6 in the USA., and none in Canada. Drilling operations related to exploration for hydrocarbons in the Yukon, District of Mackenzie and the Arctic Islands, as well as environmental studies in connection with highway and pipeline projects, are producing basic data on groundwater occurrence, at least for some areas of northern Canada. A number of theoretical and experimental studies are underway to determine the influence of permafrost on groundwater flow systems, and of groundwater movement on permafrost distribution (Harlan, 1971, 1972, 1974). None of these studies have quite reached the stage at which they can be applied in the search for water-supplies from aquifers in the permafrost region, or for adequate prediction of the interaction between engineering developments (roads, pipelines, etc.) and groundwater flow systems in areas with permafrost.

The solution of actual groundwater problems at specific locations in the permafrost region must therefore rely, for some time in the future, on methods and approaches developed for the somewhat different conditions prevailing in the more temperate regions of the country. Accounting for and dealing with the presence of permafrost will often be empirical, on the basis of trial and error, rather than on the basis of adequate understanding of the physical system. In the following sections an attempt is made to review the knowledge of groundwater occurrence in northern Canada, and to indicate the, often restrictive or adverse, role played by permafrost in groundwater problems and by groundwater in engineering problems in the North.

Information contained in this report was gathered from both published and unpublished sources. Cooperation in various forms by Northern Engineering Services Ltd., Calgary; Aquatic Environments Ltd., Calgary; Terrain Sciences Division, Geological Survey of Canada, Calgary; Fisheries Service, Environment Canada, Vancouver; and Water Management Service, Department of

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The solution of actual groundwater problems at specific locations in the permafrost region must therefore rely, for some time in the future, on methods and approaches developed for the somewhat different conditions prevailing in the more temperate regions of the country. Exploration for and dealing with the presence of groundwater will often be conducted, on the basis of trial and error, rather than on the basis of adequate understanding of the physical system. In the following sections an attempt is made to review the knowledge of groundwater occurrence in northern Canada, and to indicate the, often restrictive or adverse, role played by permafrost in groundwater problems and by groundwater in engineering problems in the north.

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Indian Affairs and Northern Development, Yellowknife and Whitehorse, is gratefully acknowledged.

Evidence for occurrence of groundwater flow

The existence of active groundwater flow systems can be deduced from field observation of natural groundwater discharge phenomena. As in more southern latitudes these include springs, baseflow in rivers, seasonal variations in dissolved-solids concentrations in riverwater, ponds and lakes with accumulations of mineral precipitates, and halophytic vegetation areas. In addition to these the presence of open-water areas in rivers throughout the winter, the growth of aufeis deposits, and the presence of active open-system pingos also indicate discharge of groundwater of varying magnitude.

Springs with water temperatures ranging from +54°C to -2.9°C, total-dissolved-solids (TDS) concentrations ranging from about 50 to more than 75,000 ppm (parts per million), and discharge rates from 1 to more than 100 l/sec., have been observed during various reconnaissance studies in northern Canada (e.g. Beschel, 1963; Brandon, 1965). Examples given in Table I include springs with low water temperature and TDS content (#1 and 2); with low water temperature and high to very high TDS content (#3 to 6); with high temperature and high TDS content (#7 to 9); and with high temperature and low TDS content (#10). As can be seen from Table I, the chemical composition of waters with similar TDS contents may vary appreciably (#7 and 9; #2 and 10).

The high-temperature springs, regardless of their chemical composition, may have some economic potential as sources of energy for heating purposes, in addition to their potential as tourist attractions. Boiling-water or steam sources that could be used for power generation have so far not been found in the permafrost area in Canada.

Major fresh-water springs feeding rivers in the Porcupine River and Beaufort Sea drainage areas in the Yukon (Bryan, 1973) were called thermal by Mollard (1972). Although their temperatures are appreciably higher than the mean annual air temperatures in the region, the designation as thermal could create an erroneous impression regarding their water temperatures (Table II). Only one group of springs, on Cache Creek in the Richardson Mountains, with water temperatures between 15 and 17°C, is properly classed as thermal.

Water discharged by springs during the winter maintains open-water reaches in a number of northern rivers. Winter open water in the Fishing Branch of the Porcupine River may

TABLE I

CHEMICAL ANALYSES FOR SELECTED SPRINGS IN NORTHERN CANADA (in ppm)

Source	1 Fishing Branch Springs at Bear Cave Mountain	2 Upper Babbage River Springs	3 Willowlake River Spring, 8 miles above mouth	4 White Sulphur Springs, south of Hanna River	5 "Big Section" Creek Spring
Location	66°30'N/ 139°20'W	68°38'N/ 139°20'W	62°39'N/ 122°57'W	65°37'N/ 127°48'W	63°42'N/ 123°50'W
Date Sampled	21-7-72	27-6-73	22-6-73	24-6-73	23-6-73
Temperature, °C	5.3	4.8	9.5	4.5	5.0
Conductivity, µmhos/cm	316.	285.	2380.	6280.	8040.
pH, units	7.6	7.5	7.4	6.9	7.3
Dissolved oxygen	6.4	4.6	6.4	0.0	1.8
Ca	46.9	48.0	531.	638.	577.
Mg	9.5	8.3	60.	116.1	181.3
Sr	-	-	-	-	-
Na	3.5	0.9	7.5	750.	1092.
K	0.9	0.3	0.9	5.4	9.8
Li	-	-	-	-	-
Fe	0.1	< .05	0.1	< .03	4.1
Mn	0.01	< .011	0.029	0.017	0.19
Cu	0.007	< .001	< .001	< .001	< .001
Pb	0.004	< .005	< .005	< .005	< .005
Zn	0.063	0.012	0.002	< .002	0.029
HCO_3	169.6	170.8	205.	300.1	242.8
CO_3	0.0	0.0	0.0	0.0	0.0
SO_4	17.9	13.0	1264.	1810.	1696.
Cl	3.8	0.3	6.4	1156.	1852.
F	-	0.19	1.3	-	1.7
NO_3	-	0.17	0.03	-	0.02
PO_4	0.011	-	-	-	-
SiO_2	2.5	5.2	6.0	7.0	8.5
Sum	254.8	247.2	2082.	4783.	5661.

TABLE I (continued)

Source	6 Gypsum Hill Springs, Axel Heiberg Island*	7 Cache Creek Springs	8 Rabbitkettle Hot Springs	9 Takhini Hot Springs	10 MacArthur Hot Springs
Location	79°24'N/ 90°43'W	68°17'N/ 136°21'W	61°56'N/ 127°11'W	60°53'N/ 135°21'W	63°04'N/ 135°42'W
Date Sampled	18-8-62	26-6-73	13-6-73	12-7-72	24-7-72
Temperature, °C	-2.9 to +6.1	15.0	22.0	46.7	54.0
Conductivity, µmhos/cm	-	4800.	1170.	2905.	227.
pH, units	-	7.6	6.6	6.89	9.1
Dissolved oxygen	-	0.5	0.2	0.6	0.0
Ca	1823.	98.	218.	590.	1.6
Mg	346.	22.2	33.7	88.9	0.05
Sr	-	-	-	14.3	0.05
Na	27100.	908.	4.2	35.0	46.0
K	25.	20.0	4.9	8.5	1.3
Li	-	-	-	0.031	0.176
Fe	-	0.06	0.12	0.60	< .05
Mn	-	< .011	0.01	< .005	< .005
Cu	-	< .001	< .001	0.002	< .002
Pb	-	< .005	< .005	< .004	0.004
Zn	-	0.011	0.009	0.074	0.015
HCO_3	32.3	267.2	802.1	126.9	47.7
CO_3	0.0	0.0	0.0	0.0	17.3
SO_4	3995.	406.	33.0	1744.	18.2
Cl	42340.	1200.	0.7	1.3	0.8
F	-	-	0.13	3.2	7.9
NO_3	-	0.14	< .01	0.08	0.54
PO_4	-	-	-	-	-
SiO_2	-	19.0	13.0	46.0	67.0
Sum	75661.	2941.	1110.	2658.8	208.6

* From Beschel, 1963. Temperature range is given

extend over more than 30 km. The presence of such open-water reaches during the winter indicates occurrence of significant groundwater discharge.. The size of the open-water areas is a function of the water and air temperatures, the discharge rate, the gas and dissolved-mineral contents of the water, and the channel configuration.

Unless groundwater discharge during the winter enters a perennial waterbody (river or lake), it will eventually freeze at some distance downstream from the springs or seepages, forming aufeis deposits or icings of varying magnitude. The distance between the point of discharge and the point where aufeis development starts is a function of the discharge rate, water temperature, and TDS and gas contents, and of the variable conditions of air temperature, humidity and wind direction and speed. Major examples of aufeis occurrence are found in the valleys of Upper Firth River, Babbage River and Joe Creek (Table II). Smaller ones are associated with other springs in the British, Richardson, Ogilvie, Mackenzie and Franklin Mountains, and on the Yukon Coastal Plain. Some of the aufeis fields are so large that a portion of the ice may remain unmelted after a summer with below-average temperatures.

Aufeis presents temporary above-ground storage of groundwater discharge during the winter, which is gradually released to streams during the summer. The volume of ice in an aufeis deposit is a function of the discharge rate of the springs that feed it, and of the length of the freezing period. If volume and time are known, the average discharge rate can be calculated. Another approach that makes it possible to determine the approximate discharge rate Q of a spring from the surface area of an associated icing at the time of maximum build-up (F_{max}), was developed by Tolstikhin (1963). It makes use of a parameter called specific or unit aufeis area F_u, which represents the average gain in surface area, in km^2, that is supported by a unit discharge rate of one l/sec. A study of 105 springs with Q > 25 l/sec. in NE Yakutia indicated an average value for F_u of 0.012 km^2 (± 10%). These methods that were originally developed for evaluation of potential water-supply sources in Siberia, can also be used to make predictions about the maximum extent of aufeis if the discharge rates of the springs are known and if data are available on the average length of the freezing period.

Investigations of groundwater-related aufeis occurrences in northern Canada have so far been restricted to spring-discharge measurements and chemical analysis of samples for some of the springs, and preliminary airphoto interpretation. The usefulness of existing airphotos is limited because for most of the areas involved only one set of photographs is avail-

TABLE II

DISCHARGE RATES, TDS CONTENTS AND WATER TEMPERATURES FOR SPRINGS WITH ASSOCIATED OPEN WATER AND AUFEIS DEPOSITS

Location of Springs	Discharge, l/sec.*	TDS, ppm	Temp., °C	Open Water	Aufeis
Yukon Territory					
Fishing Branch	11,200 ** (t)	255	4.5 to 5.3	Yes	No
Upper Firth River	900 ** (t)	278	1.5	Yes	Yes
Joe Creek	30.4;470 (t)	195	4.0	Yes	Yes
Fish Hole Creek	69.7;898 (t)	185 - 205	4.0 to 4.5	Yes	Yes
Upper Babbage River	81.0;1400 (t)	187 - 247	4.5 to 4.8	Yes	Yes
Crow River	41.8	222 - 270	2.0 to 5.0	Yes	Yes
Fish Creek	12.4;120 (t)	250 - 253	2.0 to 3.0	Yes	Yes
"New"Creek	62.2;355 (t)	319 - 409	2.0 to 3.0	Yes	Yes
Arctic Islands					
Gypsum Hill, Axel Heiberg Island ***	3.7	75083 - 75812	-2.9 to +6.7	Yes	Yes
District of Mackenzie					
Cache Creek	345 (t)	2585 - 3158	15.0 to 17.0	Yes	Yes
Prohibition Creek	3.2	1597	7.5	Yes	Yes
Vermilion Creek	77 + 90	1223 - 2198	4.0 to 8.0	Yes	Yes
"Birch Island" Creek	129 (t)	625	3.5	Yes	Yes
Creek N. of Ochre River	19.4;150 (t)	427	4.0	Yes	Yes
Smith Creek	38.4	685	3.0	Yes	Yes
Blackwater River	28.3 + 236	634 - 895	2.5 to 3.0	Yes	Yes
Willowlake River 4 miles above mouth	12.7 + 62.8	2271 - 2295	9.5 to 12.0	Yes	No

* Measurements by Aquatic Environments Ltd., Calgary, in November, 1972 and April, 1973.
(t) denotes combined discharge from group of springs.

** Discharge data from Bryan, 1973.

*** Data from Beschel, 1963

able, taken in most cases between mid-July and mid-August. Appreciable melting has taken place by that time and many of the smaller icings are no longer present. Imagery at 18-day intervals through NASA's ERTS-I satellite enables to some extent the monitoring of aufeis melting. Limitations to the wider use of the satellite imagery in aufeis studies include: size of the smallest discernible feature is about 100 m^2; cloud cover obscures ground features; short daylight hours and low sun angle restrict the usefulness in winter; and differentiation between snow cover and (wet or dry) aufeis surface is difficult, preventing use of the imagery for monitoring of aufeis development. The earliest images obtained after snowmelt in spring will presumably indicate conservative values for maximum aufeis build-up, as some ice will already have melted from the edges of the icefield. Nevertheless, the use of satellite imagery does appear to have some promise in this field.

The presence of extensive spring-fed aufeis areas in a river basin usually will have some seasonal influence on surface-water quality. During gradual freezing of spring water flowing over aufeis, TDS concentrations increase gradually in the remaining water, until saturation is reached, and precipitation of minerals starts. The final dissolved material is precipitated or included as brine inclusions in the ice when the last of the water is frozen. As runoff channels over the ice change location continuously, the distribution of precipitated minerals in the aufeis deposit will not be uniform. During melting the easily soluble components (NaCl, KCl) go back into solution immediately, while $CaCO_3$, $CaMg(CO_3)_2$ and $CaSO_4$ are redissolved at a considerably slower rate. This leads to a slush of mineral precipitate on the surface and around the edges of a melting aufeis field. Most of the precipitate must eventually be carried off in suspension or in solution because no accumulation of mineral precipitate has yet been found at any aufeis locations investigated. Table III presents a comparison of chemical analyses of springwater with those of random samples of associated aufeis, meltwater and mineral precipitate. The results indicate that considerable differences in composition can occur between springwater and the meltwater from associated aufeis deposits.

Aufeis or icings related to groundwater discharge from the active layer normally start forming early in winter and in many cases development stops before midwinter, either because no further water is available, or because outlets freeze over. The surface area and volume of such icings are generally small in comparison to those of aufeis deposits fed by perennial springs.

TABLE III

A. ANALYSES OF SPRING WATER AND OF ASSOCIATED AUFEIS AND MELTWATER (in ppm)

Source	TDS	Ca	Mg	Na+K	Cl	SO_4	HCO_3	SiO_2
Fish Hole Creek								
Springwater	184.7	35.0	6.9	1.0	0.4	14.0	123.2	3.9
Aufeis	39.3	7.5	0.8	1.8	1.1	2.5	25.6	-
Meltwater	88.0	17.0	3.3	0.6	0.2	9.5	57.3	-
Crow River								
Springwater	269.8	59.0	5.0	2.3	1.2	14.0	184.2	3.9
Meltwater	40.6	9.1	0.6	0.3	<0.1	2.4	29.2	-
"New" Creek								
Springwater	312.0	56.0	8.8	19.0	13.0	48.0	162.3	4.8
Meltwater	249.0	39.0	7.7	20.8	17.0	62.0	102.4	-

B. ANALYSES OF MINERAL PRECIPITATE COLLECTED FROM AUFEIS (in % weight)*

Source	$CaCO_3$	$CaMg(CO_3)_2$	$CaSO_4 . nH_2O$	$SrCO_3$	Organic Matter	SiO_2	Al_2O_3	Others
Fish Hole Creek	77.6	3.7	1.9	0.7	2.7	9.6	0.9	3.0
Crow River	69.5	5.5	2.4	0.0	4.0	16.3	1.9	1.4
"New" Creek	90.0	3.7	2.1	0.3	1.8	0	0	2.0

* Most likely mineral composition on the basis of chemical and x-ray analyses. SiO_2, Al_2O_3 and "others" (includes FeO, Na_2O, K_2O and small percentages of CaO) probably represent quartz and clay minerals. Part of these, as well as the organic matter, are derived from windblown material incorporated in the ice.

Groundwater discharge often provides a significant contribution to streamflow, even in cases where no springs, open-water areas or aufeis deposits reveal its presence. Studies of baseflow characteristics, and of seasonal changes in dissolved-solids concentration in the river water will usually provide an indication of the magnitude of the groundwater component. Existing streamflow records suggest that the minimum mean monthly discharge is very close to zero in many basins in the zone of continuous permafrost, mainly because most of the groundwater discharge is stored as aufeis. In the zone of discontinuous permafrost it may range from 1.0 to 5.0 $l/km^2.sec$; values over 5.0 $l/km^2.sec$ are indicative of feeding by discharge from lakes.

In many northern rivers the inverse relation between river discharge rate and dissolved-solids concentration that is usually found in more temperate regions, does not apply. The discharge of groundwater from subpermafrost sources, through taliks, may be relatively constant in rate, TDS concentration and temperature. Discharge from shallow aquifers and from the active layer, however, is distinctly seasonal in character and the largest contribution from this source will not take place until thawing of the ground is well under way. Depending on the time of the year, different rating curves for river discharge vs. TDS concentration may have to be used to derive representative figures for groundwater discharge.

Local variations in dissolved-solids load along a reach of a stream at any one time usually result from addition of groundwater discharge, of different composition, to water already flowing in the stream channel. This point is illustrated by Figure 1, for Vermilion Creek, a small tributary of Mackenzie River originating in the Franklin Mountains southeast of Norman Wells. Hitchon *et al.*(1969) have described regional variations in river-water composition in the Mackenzie River drainage, which they attributed to regional differences in rate and composition of groundwater discharge.

Small lakes and ponds in areas of low relief and along the base of some mountain ranges do reveal evidence of discharge of mineralized groundwater: high concentrations of dissolved-solids, and accumulation of mineral precipitates, the latter partly *via* the shells of gastropoda, molluscs, etc. Examples are given in Table IV. It is likely that these as well as other ponds and lakes with water of lower mineral content, are also fed by discharge from shallow aquifers. Only the discharge sources with reasonably low dissolved-solids content may be of interest as potential sources of water supply; all of them are no doubt of interest in terms of their potential for creating engineering problems.

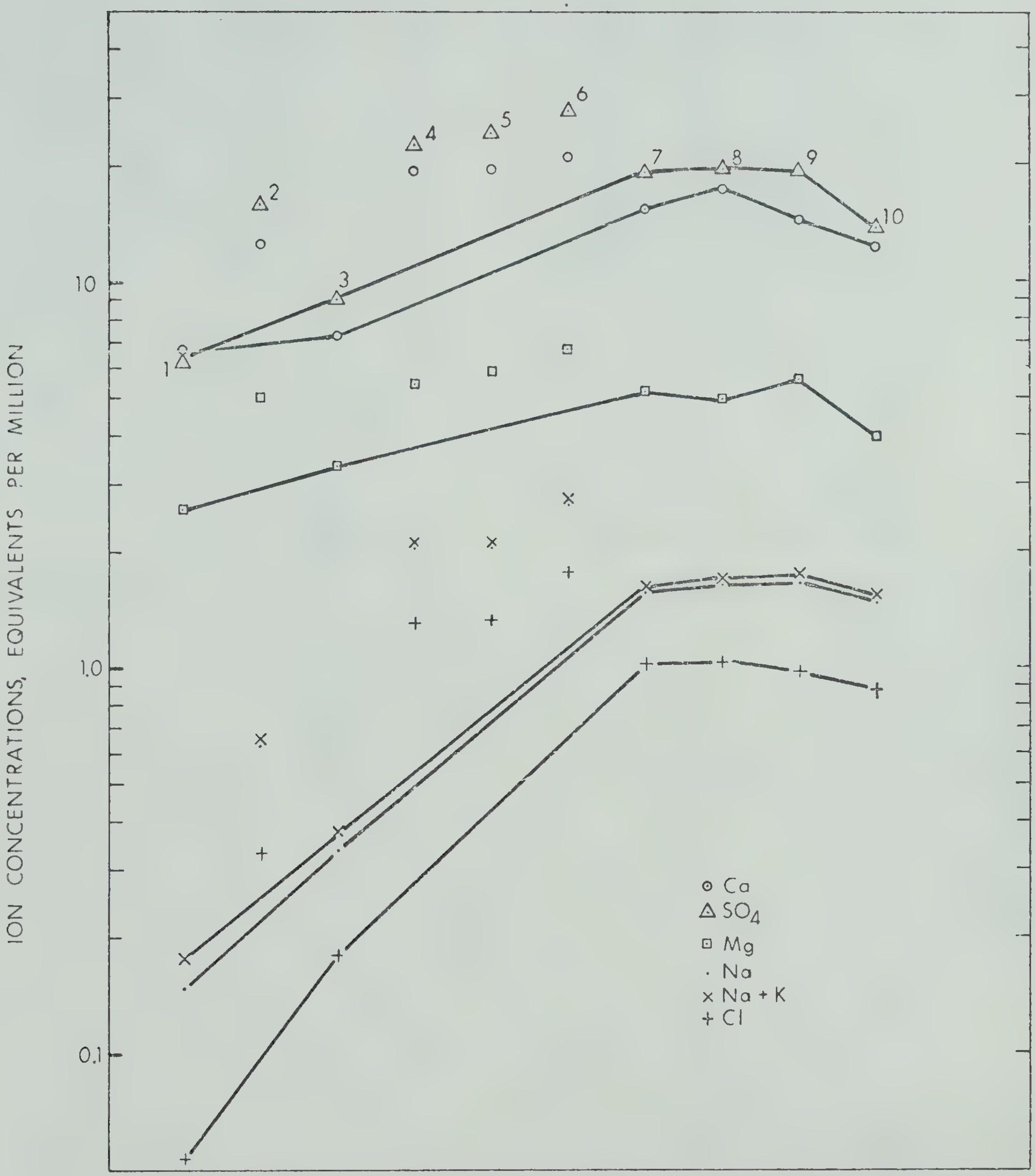

Figure 1. Chemical composition of springwater and variation of water chemistry in Vermilion Creek, District of Mackenzie, N.W.T. 1- Vermilion Creek above springs; 2- Iron Spring; 3- Vermilion Creek between Iron Spring and Sulphur Springs; 4- "Freshwater" Spring; 5- Small Sulphur Spring; 6- Big Sulphur Spring; 7- Vermilion Creek, 100 yards below Sulphur Springs; 8- Vermilion Creek, 200 yards below Sulphur Springs; 9- Vermilion Creek near proposed pipeline crossing; 10- Vermilion Creek at mouth. (No horizontal scale is implied)

TABLE IV

CHEMISTRY OF POND WATER AND OF ASSOCIATED MINERAL PRECIPITATES

A. Water Analyses (in ppm).

Source	TDS	Ca	Mg	Na+K	Cl	SO_4	HCO_3	SiO_2
Spring area on north side of Bulmer Lake	21,237	456	251	7092	9800	3175	456	4.7
Shallow pond on CNT line 30 miles N.W. of Norman Wells	1,554	387	27.1	18.9	18.0	948	151	2.7
Shallow pond 9 miles south of Smith Creek	130	25.1	3.0	1.6	1.6	5.8	85.0	7.7

B. Mineral Analyses (in % weight)*

Source	$CaCO_3$	$CaMg(CO_3)_2$	$SrCO_3$	$CaSO_4\,nH_2O$	Na_2SO_4	NaCl	Organic Matter	SiO_2	Al_2O_3	Others
Bulmer Lake Crystals on dry surface	10.8	1.1	-	-	80.2	6.8	-	1.1	-	-
Marl surface layer	78.4	7.8	1.1	3.3	-	-	2.9	4.9	0.7	1.8
Dark grey flakes from elevated mounds	86.0	6.9	0.3	4.6	-	-	1.6	-	-	1.2
Yellow grey marly material from pond on CNT line	78.7	5.5	-	3.3	-	-	8.3	2.8	-	1.4
Calcified vegetation from pond south of Smith Creek	56.4	4.1	-	4.3	-	-	32.8	2.1	0.1	0.1

* Most likely mineral composition on basis of chemical and x-ray analyses. SiO_2, Al_2O_3 and "others"(includes FeO, Na_2O and K_2O) probably represent silicate minerals brought in by surface runoff.

A last phenomenon to be mentioned in connection with groundwater discharge are the ice-cored mounds known as open-system pingos, about 500 of which have been mapped by Hughes (1969) in the Yukon. They are mainly confined to narrow valleys outside the limits of Wisconsinan glaciation where permafrost is continuous but relatively thin, and where a small but continuous supply of groundwater is available. It is likely that gradual growth of ice lenses by freezing of seasonally or continually supplied groundwater is responsible for the formation of these domelike structures (Holmes *et al*, 1968). This particular possibility may warrant their further study in the light of potential influence of chilled-gas pipelines on the movement of subsurface waters.

Groundwater as a Source of Water Supply

Groundwater in alluvial and glacio-fluvial deposits provides an adequate source of supply for a number of settlements in the zone of discontinuous permafrost (Brandon, 1965). Within these deposits the distribution of permafrost is affected by patterns of recent river channel migration and present proximity to bodies of water (river channel, lakes, ponds). Furthermore, in the more northern areas only deposits underlying south facing slopes may be relatively free from permafrost. The permability of the deposits underlying lakes and ponds will often be too low to permit development of adequate water supplies.

Quality of the water appears usually to be excellent in the alluvium of larger rivers, as well as in alluvial fans and some eskers. The water is generally of the calcium-bicarbonate and/or sulfate type. TDS concentrations ranged from less than 100 to about 1300 ppm in supplies from such sources listed by Brandon (1965). The presence of iron, manganese and dissolved organics may be a problem in alluvial aquifers associated with smaller streams and with lakes or ponds.

Proximity of the freshwater - saltwater boundary and the potential intrusion of seawater during production of groundwater and during storm tides are a deterrent to development of groundwater supplies from alluvial deposits in coastal areas in the permafrost region. Available supplies are usually high in sodium and chloride content.

Alluvial and glacial deposits may well be the only source for groundwater supplies in large areas of the Canadian Shield in northern Canada. Movement of groundwater in the crystalline rocks of the Shield is restricted to weathered zones, fracture systems and faults. All of these generally decrease rapidly in effectiveness with depth. Where found the water

may be of excellent quality.

Tertiary sands and gravels, non-marine basal-Cretaceous sandstones, as well as sandstones, limestones and dolomites in Paleozoic formations constitute additional potential sources of groundwater supply. The non-carbonate rocks usually possess either intergranular or fracture permeability; in the carbonate rocks both fractures (joints etc.) and solution openings may provide part of the available permeability. Solution of carbonate rocks and of evaporite deposits (halite, anhydrite or gypsum) is responsible for the often high Ca , HCO_3, SO_4, Na and Cl concentrations in water obtained from bedrock. In a number of cases high fluoride concentrations have also been found (Table I).

In the sedimentary basins in northern Canada groundwater flow systems extend to great depths. Flow rates become progressively slower with depth and the long residence times, as well as the availability of soluble minerals, lead to increasingly high mineralization. Total-dissolved-solids contents reach as high as 300,000 ppm, with up to 183,000 ppm chloride and as much as 8,000 ppm bicarbonate and sulfate. Calcium concentration may exceed 25,000 ppm. The dissolved-solids content is seldom less than 3,500 ppm in these basins, even in the sub-permafrost water from shallower formations (Williams and van Everdingen, 1972).

The groundwater flow systems in the mountainous areas of northern mainland Canada may benefit from slightly higher rainfall and somewhat higher recharge into coarse unconsolidated deposits protected from deep freezing by adequate snowcover. High hydraulic gradients, causing relatively rapid flow and short residence times, result in freshwater discharge in a number of areas. Lack of water available for recharge may prevent development of extensive groundwater flow systems in the mountainous portions of the high arctic. Some groundwater discharge in the younger sedimentary basins in the Arctic Islands is probably derived from continuing slow compaction of fine-grained sediments. High concentrations of dissolved solids make this type of groundwater of little value for water supply. The high NaCl content and high Na/K ratio in water of Gypsum Hill Springs on Axel Heiberg Island (Beschel, 1963) are likely caused by solution of halite which is presumably present, but not showing, in a number of evaporite diapirs.

Problems in developing water supplies from any source in the north are partly related to the presence of permafrost, and partly to the severity of the climate. Permafrost restricts the extent of aquifers, both vertically and laterally, and it may present problems during drill-

ing and maintenance. Deep freezing during the winter affects aquifers in the active layer and in taliks by reducing and in some cases eventually cutting off the supply of water to the area surrounding the well. This leads to seasonal reduction of production and, in extreme cases, drying-up of wells later in the winter.

Occasionally instances are encountered where water in taliks, or in the unfrozen zone between the active layer and the top of the permafrost, or in unfrozen pockets in the permafrost (cryopegs), or below the permafrost, is under high to very high pressure. This can lead to blowouts that may be difficult to control, because the discharging water will tend to thaw the surrounding frozen ground. However, some of these blowouts may be shortlived as a result of a restricted extent of the aquifer. A blowout of undercooled water from a cryopeg generally is very shortlived, but could result in almost instantaneous freezing of the tools in the hole.

Groundwater is used as a source of watersupply on a year-round basis in Pine Point and Edzo in the Northwest Territories, and in Whitehorse, Dawson City and some of the smaller settlements along the Alaska and Klondike Highways in the Yukon. Seasonal use is made of groundwater in Fort Providence, Jean Marie River, Fort Simpson, Fort Liard, Nahanni Butte, Wrigley, Fort Norman and Fort Good Hope. Most of these are located in the zone of discontinuous permafrost; some like Dawson City, make use of induced infiltration of river water by pumping from river alluvium. Detailed information on location, type and quality of some of the groundwater supplies in northern Canada was published by Brandon (1965). Additional information on groundwater occurrence, collected in the course of mining operations and petroleum exploration, has apparently not yet been compiled on a regional scale.

Few major industrial water supplies are obtained from groundwater in the permafrost region. An example is the Cominco mill at Pine Point which uses approximately 18,000 m^3 per day. A further 157,000 m^3/day is pumped from dewatering wells around the company's open-pit mine. These large withdrawals, rather than the 1,260 m^3/ day used by the town of Pine Point, could well be responsible for a steady decline in waterlevels observed since 1968 in the Pine Point town wells. The decline in waterlevel is apparently accompanied by a gradual increase in mineralization of the water.

In view of the gradual increase in demand for dependable year-round water supplies in northern Canada, potential water supply aquifers should be protected from any adverse

effects of developments in the vicinity, as well as from contamination by waste disposal operations. Recharge areas of such potential water-supply aquifers should be protected from the influence of any practices that may result in reduction of recharge rates or introduction of harmful substances.

The same applies to areas where major groundwater discharge maintains open water in northern rivers during the winter. Such open water in rivers of the Porcupine and Beaufort Sea drainage areas has an important role as overwintering and/or spawning areas for certain fishspecies (Bryan, 1973). Although further study of the groundwater system will be needed in these areas, efforts should also be directed at defining what constitutes significant adverse effects on either the groundwater supply or the fish population.

Engineering Problems Caused by Groundwater

The occurrence of groundwater discharge may have an adverse effect on the construction, operation and maintenance of roads, railroads, pipelines, buildings, etc. In addition to normal problems related to groundwater discharge (quick conditions, slope failures, frost heaving, ponding and flooding) engineering development in the permafrost area may run into "northern" groundwater problems. Some of these are natural, while others are induced by the development and these are the most difficult to predict for any given situation.

The most obvious natural problem occurs when a road or pipeline has to be built across a natural discharge area where no alternative routing is available. Measures will be needed to prevent damage from quick conditions and erosion; to prevent or divert discharge that causes aufeis; or to prevent aufeis from encroaching on the right-of-way. It may be useful to point out at this stage that development of aufeis or icings from groundwater discharge is not restricted to the permafrost area. It will occur wherever discharge takes place under the appropriate combination of conditions of water temperature, mineralization, flow rate, air temperature, and slope and length of channel to a major water body. As pointed out earlier, the source of the groundwater has a definite bearing on the potential severity of the problem. Icings fed by water from the active layer often stop growing before mid-winter; most icings fed by perennial karst-type springs or by subpermafrost water will keep growing as long as mean daily temperatures are below freezing. The latter therefore are much more difficult to deal with than the former.

MacKay (1973, p. 10) stated that ".. the omission of a specific study on aufeis (icings) simply reflects our view that the present distribution of the phenomenon is relatively insignificant in terms of pipeline construction". However, the present distribution of aufeis is not known in detail, even along the most likely potential pipeline routes, and data on growth rates, maximum extent and dissipation rates are lacking.

Development of transient pressures in water-bearing materials between the top of the permafrost and an advancing freezing front in the active layer may be responsible for a number of smaller aufeis deposits fed by active-layer discharge. Such transient pressures could also influence the stability of slopes during seasonal freezing and thawing. Little is known about this aspect. Similarly, seasonal pressure increases, and reduction in areal extent of discharge areas by gradually encroaching frost can be expected to lead to instability and development of quick conditions, at least in some cases. Again, information that would enable evaluation of this potential problem is lacking.

Engineering development often leads to local changes in groundwater flow patterns that result in the creation of new discharge locations. Wherever this happens, man-made groundwater problems usually follow. Examples include groundwater discharge and associated aufeis development and potential slope failures in deep cuts for roads or railroads; groundwater discharge from unfrozen waterbearing material as a result of melting of thin overlying permafrost induced by stripping of vegetation; and melting of permafrost as a result of ponding of natural or induced groundwater discharge.

When a heated oil pipeline is buried in a trench through waterbearing material, the trench fill may form a conduit for groundwater flow. This can lead to erosion of the trench fill. Introduction of a chilled-gas pipeline in waterbearing material, on the other hand, will give rise to development of ice-lenses, which may be a continuing process if a steady supply of groundwater is available. The consequences of this will vary, depending on local conditions; jacking of the pipeline appears to be an unavoidable result. Other effects could include diversion of groundwater flow by the frozen-ground barrier, with resulting discharge of groundwater, potential quick conditions, ponding of discharge and subsequent melting of permafrost (thermokarst), and growth of aufeis during the winter.

The conditions that lead to serious groundwater problems may be present in a limited

number of places only. The potential problems are, however, serious enough to warrant detailed study. Research is needed to develop adequate techniques for identification and evaluation of, existing and potential groundwater-discharge problems in and near construction areas during the route and site selection stage. Use of aerial photography, remote sensing and satellite imagery will all have to play a role in this as part of field, laboratory and model studies of the geologic, hydrologic, topographic and climatic parameters involved. Considerable savings in construction, operating and maintenance costs will result from early recognition and possible avoidance of problems related to natural or induced groundwater discharge. Studies of frost-heaving and thaw-consolidation effects in porous materials will have to take the potential presence of active groundwater flow into account before reliable predictions of terrain performance can be made.

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